Commentary

Did Ebola emerge in West Africa by a policy-driven phase change in agroecology?
Ebola's social context
The ongoing outbreak of human Ebola virus in West Africa, the largest and most extensive recorded, began in forest villages across four districts in southeastern Guinea as early as December 2013 (Baize et al, 2014; Nishiura and Chowell, 2014). The epidemic subsequently spread across Guinea, Liberia, and Sierra Leone, including to capital cities Conakry and Monrovia, before infiltrating Nigeria and Senegal. With infections at this writing newly diagnosed off-continent, the outbreak represents a significant enough threat that the World Health Organization declared it a Public Health Emergency of International Concern (Briand et al, 2014).

Bausch and Schwarz (2014) hypothesize that the virus initially spilled over in Guinea as a result of a combination of national economic and political impacts upon the first epicenter's forest community. Poverty drives forest encroachment, the infected present at inadequate medical facilities amplifying transmission, and impoverished countries are buffeted by a cascade of logistical failures extending out from the outbreak itself to the very basics of societal function, including failing to provide even enough food.

The shifts in land use in Guinée forestière where the virus originated are also connected to the kinds of governmental policy promoting neoliberal structural adjustment that, alongside divesting public health infrastructure, open domestic food production to global circuits of capital (Moseley et al, 2010; Wallace et al, 2014; World Bank, 2014). Under the newly democratized Guinean government, the British-backed, Nevada-based Farm Land of Guinea Limited, now of Africa, secured 99-year leases for two parcels totaling nearly 9000 hectares outside the villages of N'Dema and Konindou in Dabola perfecture, where a secondary epicenter developed, and 98 000 hectares outside the village of Saraya in Kouroussa prefecture (Farm Lands of Guinea, 2011). The new acquisitions, a symbolic start, are to be developed for maize and soybean. The Ministry of Agriculture has tasked the company to survey and map an additional 1.5 million hectares for third-party development.

International deals represent the latest in a series of postcolonial efforts to increase agricultural production in Guinea, such as in rice and coffee, including in Forested Guinea (Morris et al, 2009). Bausch and Schwarz (2014) characterize the area as a mosaic of small and isolated populations of a variety of ethnic groups that hold little political power and receive little social investment. Its economy and ecology are also strained by thousands of refugees from civil wars in neighboring countries. The forest is subject to the tandem trajectories of accelerating deterioration in public infrastructure and concerted efforts at private development dispossessing smallholdings and traditional foraging grounds for mining, clear-cut logging, and increasingly intensified agriculture.

Relationships across global production, deforestation, and development are rarely direct or deterministic, however (Bergmann, 2013). In-country, complex combinatorials of ownership, lobbying, popular protest, and governance foreign and domestic imprint upon local outcomes (Mendick, 2013). Twice in 2007−08, when commodity speculation drove up food prices worldwide, Guineans at large, objecting to shortages and high prices, organized general strikes that forced the military government at the time to block all exports, including agricultural, forestry, livestock, fisheries, and petroleum products (Berazneva and Lee, 2013).

A palm oil hypothesis

Historically, new epidemiologies shape and are shaped by such contingencies (Watts, 1997). By one hypothesis Ebola's latest spillover took place by way of a phase change in the local agroeconomics of oil palm *Elaeis guineensis*.

Natural and semiwild groves of different oil palm types *dura*, *pisifera*, and *tenera* have long served as a source of red palm oil in Forested Guinea (Delarue and Cochet, 2013; Madelaine et al, 2008). Contrary to prelapsarian fantasies of hunting–gathering, forest farmers have been cultivating oil palm in one form or another for hundreds of years. Fallow periods, however, were reduced over the 20th century from twenty years in the 1930s to ten by the 1970s, and still further by the 2000s, with the added effect of increasing grove density.

Other crops are grown in the forest too, of course (Fairhead and Leach, 1996; Madelaine et al, 2008). Regional shade agriculture includes coffee, cocoa, and kola. Slash-and-burn rice, maize, hibiscus, and corms of the first year, followed by peanut and cassava of the second, and a fallow period, are rotated through the agroforest. Lowland flooding supports rice. Rotation carries cultural water other than functional crop succession, also including food security, land tenure, labor availability, and regional price fluctuations (Delarue and Cochet, 2013).

The key point is that, in spite of increasing intensification, production sans finance capital can still be classified here as agroforestry.

Yet, as ever, the forest is again changing. With two million hectares of natural and traditionally cultivated stands, Guinea, trailing even Liberia's weak sector, recently began a push toward commoditizing oil palm in the face of cheap imports from Asia (Carrere, 2010; Ferrand et al, 2012). As of 2007, government plans included expanding family and industrial production to 15 000 hectares and 84 000 tons of palm oil by 2015, more than half of the latter to be produced by Forested Guinea plantations (Carrere, 2010).

The Guinean Oil Palm and Rubber Company (SOGUIPAH) founded by the state in 1987 began along the lines of a parastatal cooperative, since developing into a full-fledged state company (Delarue and Cochet, 2013). SOGUIPAH is leading regional efforts that began in 2006 to develop plantations of intensive hybrid palm for commodity export. The company has economized palm production in Yomou prefecture, south of the outbreak area, by contract farming, negotiating land requisition, organizing supply chains, franchising a production model, and, backed by police, expropriating farmland, the latter intermittently setting off violent protest. In 2011 villagers were run off their rice, coffee, and rubber fields, and forced to find refuge in a church in Nzérékoré, the provincial capital (AFP, 2011).

International aid has accelerated the transition. An industrial palm mill financed by the European Investment Bank permitted SOGUIPAH four times the capacity of its previous mill (Carrere, 2010). The new mill ended the artisanal extraction that as late as 2010 provided local populations with full employment. The subsequent increase in seasonal production has at one and the same time led to harvesting above the mill's capacity and operation below capacity off-season, leading to a conflict between the company and 2000 of its now partially proletarianized producers and pickers, some of whom insist on processing a portion of their own yield to cover the resulting gaps in cash flow. Contractors who insist on processing their own oil during the rainy season now risk arrest.

Discipline is also imposed by the biology of the industrialized tree. Producers who break their contracts are left with F2 that produce only 60% the oil of first-generation seeds provisioned by the company (Delarue and Cochet, 2013).

The new economic geography also instantiates a classic case of land enclosure, turning a tradition of shared forest commons toward expectations that informal pickers working fallow land outside their family lineage will obtain an owner's permission before picking palm (Carrere, 2010; Madelaine, 2005). Concurrently, some of the smallholders who have

remained independent have adapted to the new environment. Farmers surveyed around the village of Nienh, south of the initial outbreak, preferred planting hybrid palm in monoculture slash-and-burn for increased oil production and income, and for the private control of a resource and the land under it (Madelaine et al, 2008). SOGUIPAH has had additional effects on production in areas where it claims no plantations or contractors, including in technology transfer and upon commodity prices (Delarue and Cochet, 2013).

The agroeconomic shifts in all their complexities appear to interpenetrate the forest's epizoology.

The earliest documented cases of the outbreak in West Africa appear to be a two-year-old village boy and his three-year-old sister north of Guéckédou, a town of 200 000. But the focus on an index case—patient zero—may miss the point. Ebola may have been circulating for years, something Hewlett and Amola's (2003) work in Uganda suggests local populations may even have recognized. Indeed, Schoepp et al (2014) found antibodies to multiple species of Ebola, particularly the Zaire strain, in patients in Sierra Leone as far back as five years ago. Phylogenetic analyses of the virus's own genome date the lower bound of Zaire Ebola's entry into West Africa a decade ago (Dudas and Rambaut, 2014; Gire et al, 2014).

Figure 1 shows an archipelago of oil palm plots in the Guéckédou area, the outbreak's apparent ground zero. Land use appears as a mosaic of local villages surrounded by dense vegetation interspersed with fruit-tree plantations, an environment also suitable for frugivore bats (*Pteropodidae*), a key Ebola reservoir, and other small crop-raiding species. Shafie et al (2011) document a variety of disturbance-associated fruit bats *attracted* to oil palm plantations. Bats migrate to oil palm for food and shelter from the heat while the plantations' wide trails permit easy movement between roosting and foraging sites. Oil-palm picking in the area occurs year-round, but the biggest push takes place at the start of the dry season when multiple Ebola outbreaks have begun across the Sub-Sahara (Bausch and Schwarz, 2014; Carrere, 2010).

Even at the western edge of their traditional range *Pteropodidae* are likely to display the kind of plastic biogeography migratory waterfowl have demonstrated feeding on waste grain hundred kilometers north of their destroyed natural habitat (Cooke et al, 1995). Leroy et al (2009) tracked Ebola transmission in the Democratic Republic of Congo to massive hunting during the annual fruit bat migration up the Lulua River, including of the hammer-headed bat (*Hypsignathus monstrosus*) and Franquet's epauletted fruit bat (*Epomops franqueti*), two of the three species likely to be Ebola reservoirs. Bats occupied the outbreak area for several weeks, roosting in fruit trees and the palm trees of a massive abandoned plantation bats had been visiting for half a century.

Bushmeat need not be a default explanation for any given outbreak, however. Field (2009) noted that deforestation, including from oil palm planting, changes foraging behavior of the flying fox, fixating now on horticulture crops, and expands interfaces among bats, humans, and livestock. Fruit bats in Bangledesh transmitted Nipah virus to human hosts by urinating on the date fruit of the planted palm trees humans cultivated (Luby et al, 2009).

A similar agroecology characterizes the Kailahun epicenter in Liberia. Guinea's neighbor to the south, however, hosts a different trajectory in agricultural consolidation, back to Firestone Rubber Company's first investments in 1925 and a post-WWII open door policy privatizing land across sectors, including rubber, timber, iron-ore, and diamonds (Fouladbash, 2013). More recently, alongside a longer national tradition of wage labor, international logging, mining, and agro-industrial companies, including palm oil companies Sime Darby (Malaysia), Equatorial Palm Oil (UK), Golden Veroleum (Indonesia), have partaken in large-scale land expropriation totaling a third of the country's land surface, with planned concessions pushing that total to nearly 45% (Evans and Griffiths, 2013; Murombedzi, 2014).
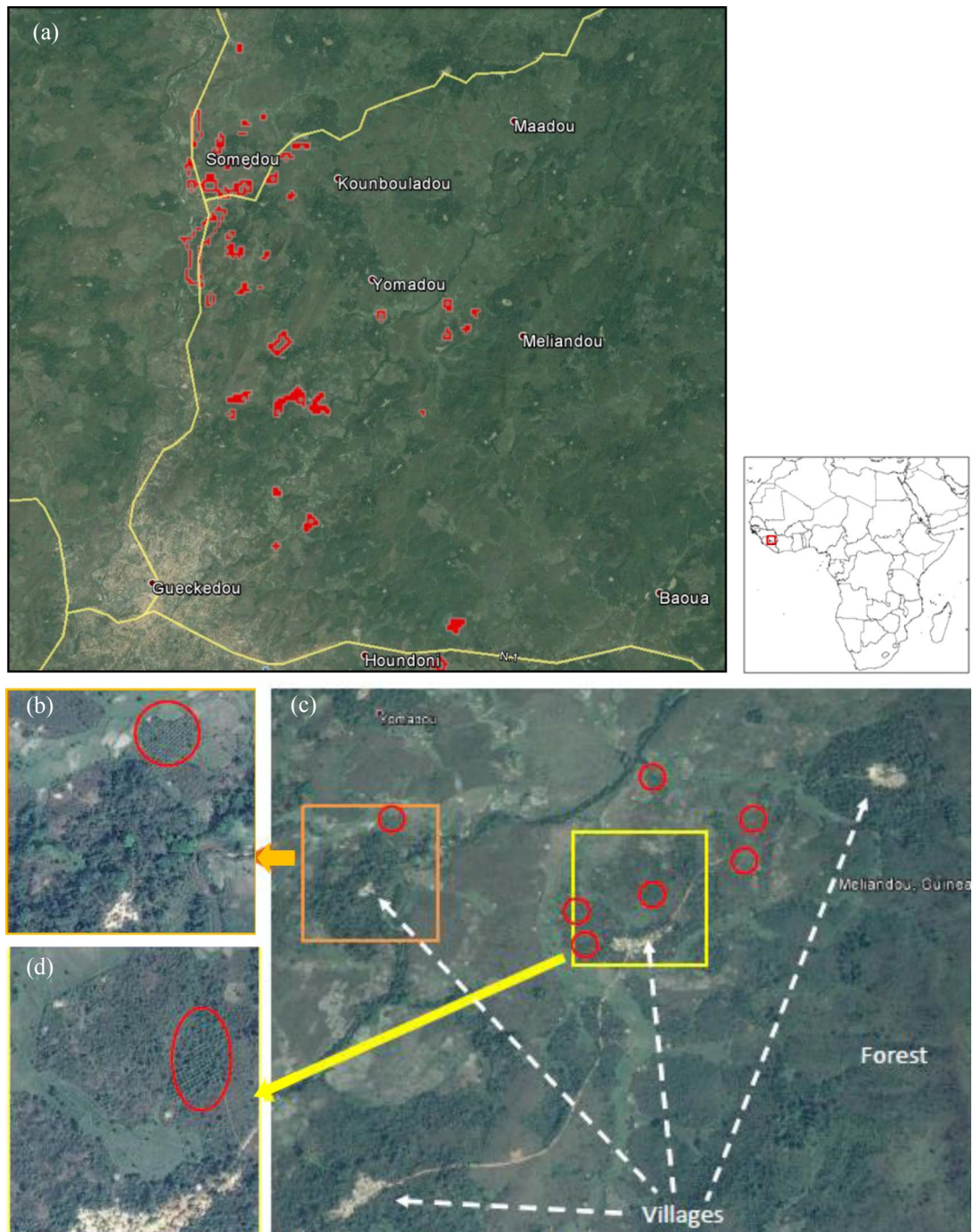
Figure 1. [In color online.] Land-use pattern in West African Ebola's putative area of origin near Guéckédou, Guinea. The characteristic landscape is a mosaic of villages surrounded by dense vegetation and interspersed by crop fields of oil palm (red) and patches of open forest and regenerated young forest. The general pattern can be discerned at a coarse spatial scale north of Guéckédou (a) and a finer scale west of Meliandou (b–d).

Development schemata look to regionalize that model (Zagema, 2011). The hot zone as a whole comprises a part of the larger Guinea Savannah Zone the World Bank describes as "one of the largest underused agricultural land reserves in the world", which the Bank sees best developed by market commercialization, if not solely on the agribusiness model (Morris et al, 2009).

A general model of epidemiological phase change

The functional relationships such economic geographies share with epidemiology have been modeled elsewhere.

Wallace and Wallace (2014) describe the sudden emergence of poliomyelitis in postwar England and Wales as the consequence of the increasing per capita affluence of its human host. The normalized extents of polio epidemics between 1940 and 1957 are a function of the millions of registered cars in the UK. The sudden availability of private travel in the UK after World War II appeared sufficient to breach the level of isolation between small focal polio outbreaks that kept the larger island 'sterilized'. The phase transition of its host's sociogeographic space triggered polio's punctuated emergence as an epidemic.

The normalized characteristic extent of an epidemic can be viewed as a classic order parameter. For polio the number of cars or for Ebola palm oil's expanding value-added network may act as smoothing agents, truncating ecosystemic barriers that interrupt chains of transmission and driving a coevolutionary socioviral system across a critical point.

Taking the perspective of Wallace and Wallace (2014), the most direct mathematical approach involves a stochastic extinction model of an exponentially growing population.

Let $N_t \geqslant 0$ represent the number of individuals of a particular pathogen 'species' at time t. The simplest possible model is given by the stochastic differential equation:

$$\mathrm{d}N_t = \alpha N_t \mathrm{d}t + \sigma N_t \mathrm{d}W_t^H \ , \tag{1}$$

where $\alpha > 0$ is a characteristic rate constant for exponential growth, σ is an index of 'noise' strength, and $\mathrm{d}W_t^H$ represents a fractional white noise process with index $0 < H < 1$. $H = 1/2$ represents ordinary white noise. Fractional white noise is defined by the covariance relation:

$$\mathrm{cov}[W^H(t), W^H(s)] = 1/2(t^{2H} + s^{2H} - |t-2|^{2H}) \ . \tag{2}$$

Taking the Ito formula expansion for $\ln N_t$, the correction factor from the added noise term gives the classic result (Zeng et al, 2013):

$$N_t = N_0 \exp\left(\alpha t - \frac{\sigma^2}{2}t^{2H} + \sigma W_t^H\right) \ . \tag{3}$$

Following Zeng et al (2013, theorem 3.1), if $0 < H < 1/2$, then the system is asymptotically explosively unstable for any $\alpha > 0$. For $H = 1/2$, if $\sigma^2 > 2\alpha$, noise-driven fluctuations will asymptotically drive the pathogen to the absorbing state of local extinction: that is, $N_t \to 0$. However, for noise defined by $1/2 < H < 1$, the system is always asymptotically stable in this sense, regardless of α.

Figure 2 shows two simulation examples for $H = 1/2$, with σ below and above criticality. For the first, below the critical index, the initial infection eventually explodes by exponential growth. For the second, just above criticality, the initial infection eventually collapses toward extirpation.

A similar stochastic differential equation approach has been used to model noise-driven criticality in physical systems (Van den Broeck et al, 1997), suggesting that a more conventional phase transition methodology might provide particular insight, as done in Wallace and Wallace (2014).

A simple spatial analysis leads to similar results. Assuming a one-dimensional diffusion-growth model:

$$\frac{\partial N}{\partial t} = \frac{\mu \partial^2 N}{\partial x^2} + \alpha N \ , \tag{4}$$
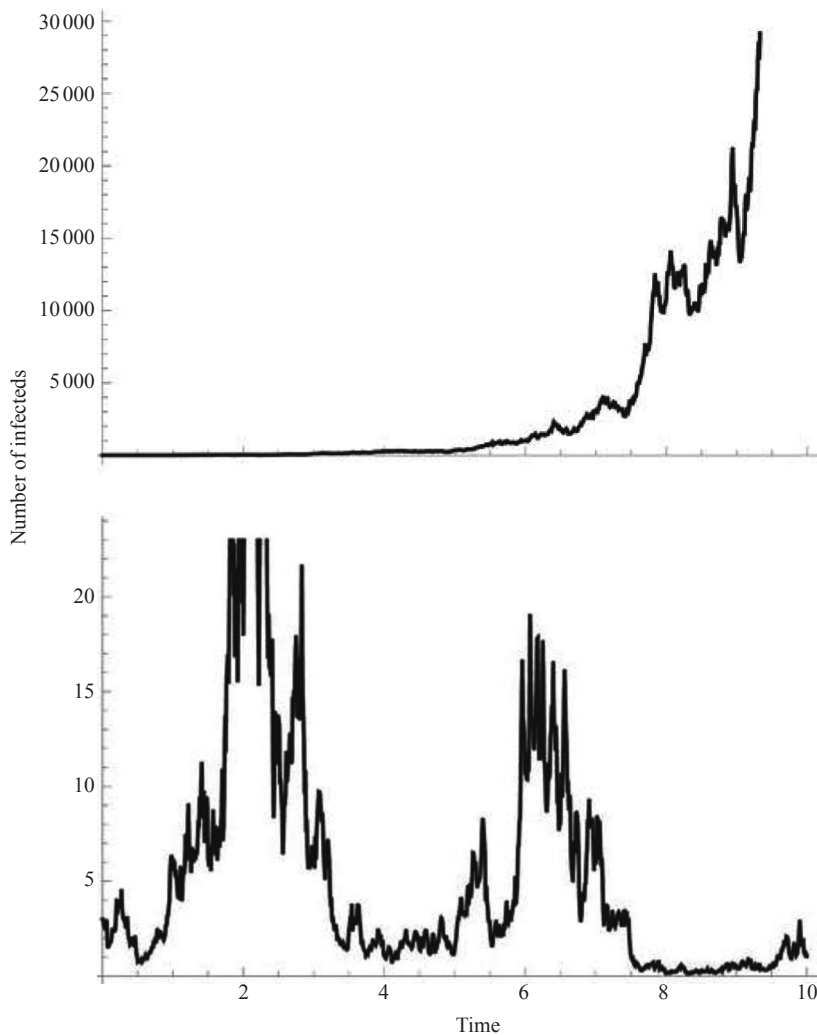
Figure 2. Simulations of equation (1) using the white noise ($H = 1/2$) ItoProcess construct in Mathematica: $\alpha = 1$, critical $\sigma = (2)^{1/2}$, initial number of infecteds, $N_0 = 3$. The upper trace has $\sigma = 0.5$, the lower has $\sigma = 1.6$. One thousand time steps. While the upper outbreak eventually reaches tens of thousands, the lower remains under 100.

where x represents distance, μ is the diffusion coefficient, and the initial patch size has length L, a Fourier series expansion leads to an exponential term in time (Okubo, 1980):

$$\exp\left[\left(\alpha - \frac{\mu\pi^2}{L^2}\right)t\right]. \tag{5}$$

Thus the infection dies out if $L < L_c \equiv \pi(\mu/\alpha)^{1/2}$. In two dimensions π is replaced by 4.81… . The circumference/area ratio grows $\propto 1/L$, so that, for small L, edge habitat, rather than patch habitat, dominates disease ecology. In general, edge habitats will not *incubate* pathogens as productively as patches (as opposed to spilling over). Indeed, a simple dimensional analysis leads to the $L_c \propto (\mu/\alpha)^{1/2}$ expression. Expansion of equation (4) to a full stochastic differential equation model, with fractional time diffusion and colored spatial diffusion, is mathematically nontrivial (Balan and Tudor, 2008).

The generality of the model opens any number of ways of operationalizing it. Again following Wallace and Wallace (2014), one might well populate both σ and H with variables beyond the stalwarts of population densities and transmission rates, instead including

governmental policies promoting neoliberal or neocolonial development, an expansion in logging, or the elimination of traditional systems of subsistence that *at the population level* previously isolated pathogens or their carriers from livestock and/or humans, even as individual spillovers may have accrued with regularity.

The details are likely to differ, of course, but we hypothesize that such large-scale shifts across anthropogenic systems will routinely trigger sudden spikes in pathogen population load. The resulting increases in circulating pathogen and their phylogenesis may produce new patterns of infection and the evolution of increased transmissibility and virulence standard niche analyses by definition miss (eg, Pigott et al, 2014). That is, changes in policy or socioeconomic structure, including the economics driving plantation farming, can 'desterilize' a natural or human ecosystem in which a pathogen has been largely held in check at a low-level equilibrium value, or simply had not previously evolved.

In the other direction, traditional or conservation agricultures can by their diversity in time, space and mode create numerous functional and physical barriers—counterintuitively, a kind of ecosystemic noise comparable to a sterilizing temperature in a physical system—limiting in a case-by-case basis many a pathogen's evolution and spread (Wallace and Kock, 2012; Wallace and Wallace, 2014).

Conclusions, caveats, and next steps
The deductive model introduced here suggests that a critical noise of environmental stochasticity can be empirically defined for each ecosystem, incorporating measures of the disease-specific barriers imposed upon pathogen evolution and propagation.

Alongside commoditizing fruit trees and the social effects of governmental policies favoring dispossession—rejuxtaposing populations of people and animal alike—by an epizoological Allee effect clear-cutting Forested Guinea may have lowered the ecosystemic 'temperature' below which Ebola can be 'sterilized' and controlled (Hogerwerf et al, 2010; Stephens et al, 1999). Indeed, the model suggests the possibility in some parameter spaces that a threshold can be lowered to such a point that no emergency intervention can drive the pathogen population low enough to burn out on its own, refuting the false dichotomy between structural and emergency interventions (eg, Osterholm, 2014).

Whether such a conundrum defines West Africa remains to be ascertained. The specifics are likely to be complex. Guinea's new agriculture is more nuanced than 'industrial' against 'smallholder' (Carrere, 2010; Delarue and Cochet, 2013; Madelaine et al, 2008). As elsewhere, including Thailand and Mexico, smallholders, farm cooperatives, and even state companies are faced with a choice as global markets shift and tariffs are removed on multinationals beginning to buy up domestic land (Moran, 2011; Walker et al, 2012; Wise, 2010). Either sell off or consolidate, scaling up to meet the competition. Even as there are presently no multinational plantations in Guinea, oil palm there represents a classic case of creeping consolidation, enclosure, commoditization, and capitalization curtailing artisanal production. So while no private companies presently plants oil palm in Guinea, by a relational geography the effects of the global market upon the local agroecology appear to be felt already.

Other explanations for Ebola in West Africa are, of course, in play. Deforestation, dedevelopment, population mobility, periurbanization, cycle migration, and an inadequate health system that failed to recognize and isolate cases may have synergistically eased the ecosystemic friction acting on circulating Ebola. The lethargy of the international response exacerbated matters once the outbreak began. A Structural One Health may be able to unify such a variety of deterministic sources under the rubric Ebola's agroecology and its failure of containment—only 900 beds are presently available across all of West Africa—arose together out of the neoliberal program (and a longer history of exploitation) (Jones, 2014;

Wallace et al, 2014). Successful intervention for a circulating pathogen in a system may call for rolling back the structural violence long visited upon the region.

The model here, itself part of the hypothesis, generalizes relationships among a (pathogen) population, its carry capacity, and stochastic noise (from a variety of possible sources) on punctuated dynamics. Ostensibly the model could be conditionalized in various ways for testing in specific systems, Ebola in West Africa included, but its simplicity here speaks to a general condition across systems, regardless of their biologies. Namely, pathogen success is fundamentally integrated with its population biological (and sociological) context.

Be that as it may, the statistical economic geographies, value-chain analyses, and dynamic socioecological niche modeling needed to test the hypothesis are welcome. Science proceeds, even as we must also recognize its difficulties. The data to test the hypothesis—eg, remote sensing of owner-coded plantations across the region, geocoded prevalences of Ebola in symptom-free bats, surveys of local epidemiological knowledge—are presently unavailable (Leach, 2014). As the present outbreak signals, however, such efforts are critical for characterizing the ecosystems on which humanity must routinely be reminded it depends.

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